Effect of Strong Magnetic Field on Temperature Distribution in Plasma Jet*†

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An experimental study of plasma jet at a low pressure was carried out to examine the influence of strong magnetic field on the temperature distribution. This is a fundamental study of the possibility that the jet can be controlled by the strong magnetic field. A magnetic field was applied to the jet in the vacuum chamber by means of a pair of superconducting coils. An optical probe was set at the middle between both coils. Argon emission spectra were measured at vertical positions to determine the excitation temperature. The measured intensity distributions were also transformed into the radial emission profile by the Abel-inversion. The radial temperature distributions were determined from the relative emission intensity. It was indicated that the excited temperature around the central part of the jet increases with the strength of magnetic and that the temperature slope toward the outside of the jet becomes obviously large as the field strength increases.

Introduction

It is promising that plasma propulsion will play an important role in the future space mission. Also, plasma is a typical functional fluid in the magnetic field [1]. Therefore, the performance of the plasma propulsion system could be expected to improve remarkably, provided that strong magnetic field can be utilized for enhancing the functions of plasma flow. Experimental studies of functional enhancement of the plasma jet in the magnetic field have previously been made to examine the effects of magnetic field on the flow [2-4]. However, data on the flow characteristics have not been obtained sufficiently under the strong magnetic field such as a superconducting magnet can generate. To realize the development of the plasma propulsion system that employs the strong magnetic field, it is important to clarify the effects of the strong magnetic field on the plasma jet and to get a better understanding of the characteristics on the plasma flow under the strong magnetic field.

From this point of view, in the previous paper [5], the behavior of argon plasma jet was observed when the strong magnetic field was applied to the jet by using a pair of superconducting coils. It was indicated from the observation that the jet radially compresses with the application of the strong magnetic field and that the high temperature region in the middle of the jet becomes much brighter with the strong magnetic field than without magnetic field. The relative line intensity measurement was also carried out to determine the excitation temperature at a fixed point on the jet center axis. It has been clarified that the excitation temperature at the measuring position increases with the strength of magnetic field.

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In the present paper, the excitation temperature distribution in the plasma jet is determined by moving an optical probe with a traverse assembly. That is, Argon emission spectra were measured at vertical positions. After the data on the emission are calibrated using the relative spectral response of the optical system used in the present experiment, the vertical distributions of excitation temperature are determined from the calibrated data for spectral response. Moreover, the vertical intensity distributions are transformed into radial emission profiles by the Abel-inversion. The radial temperature distributions are determined on the basis of the transformed profile. It is clarified from these results that the temperature distributions of the plasma jet are affected obviously by the applied magnetic field and that the plasma jet could be controlled considerably by the strong magnetic field.

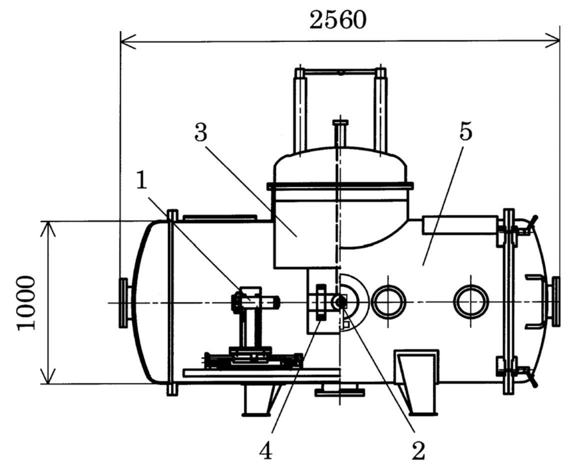
Nomenclature

A_{ji} = Einstein coefficient for spontaneous emission
B_c = magnetic flux density at the midpoint between coils in the case of both coils' operation
E_j = energy of j level
g_j = degeneracy of j level
$I(z)$ = measured spectral intensity at vertical positions
$I_c(z)$ =calibrated vertical intensity for spectral response
I_{ji} = spectral intensity of j to i transition
i_c = specified current of superconducting coil
i_s = supplied current to plasma torch
L = distance to the central axis of optical probe from nozzle exit plane of plasma torch
$\dot{m}$ = mass flow rate
p = background pressure
R = jet radius
r = radial coordinate
z = vertical position
T_{ex} = excitation temperature
$\varepsilon(r)$ = emission coefficient in the radial direction
λ_{ji} = wavelength of j to i transition

Subscripts
i = lower energy level
j = upper energy level

Experimental Setup and Procedure

The experimental setup is made up of four primary systems; that is, a plasma generator system, a superconducting magnet system, an optical measuring system and a vacuum chamber with a vacuum pump system. Figure 1 shows a cutaway view of the chamber. A plasma torch, an optical probe and a superconducting magnet are arranged in the vacuum chamber as schematically shown in this figure. The plasma torch is movable along the centerline of magnet bore. Argon gas was employed as working gas. Thermal plasma jet was generated by high intensity DC arc discharge in the chamber. The behavior of the jet was seen through three windows for observation installed on the side of the vacuum chamber. The chamber pressure was reduced to 2 Pa or less before measurements and held constant during measurements by using the vacuum pump system.

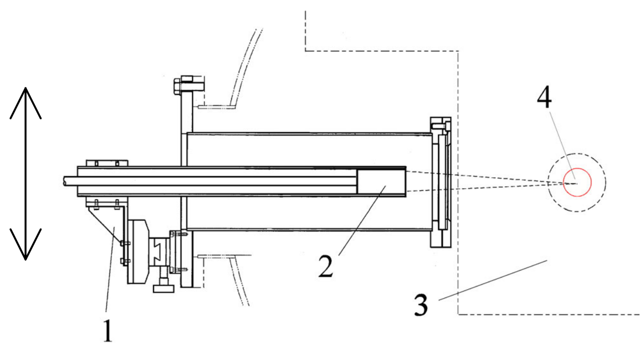


1. Plasma torch, 2. Optical probe, 3.Cryostat,
4. Superconducting coil, 5. Vacuum chamber

Fig.1 Arrangement of apparatus in vacuum chamber

Strong magnetic field was applied to the jet by means of the superconducting magnet. The magnet consists of a pair of superconducting coils. The coils are held at liquid helium temperature by the cryostat. Each coil has the same specification and can produce a field in excess of 3 Tesla. The magnetic flux density at the midpoint between coils is referred to as B_c in the case that the both coils operate. It becomes 1.5 T under the condition of maximum specified current i_c = 107.16A.

An optical probe was set at the middle between both coils. Emission from the plasma jet was collected by the lens system at the head of the optical probe. The focused point was placed on the plane involving centerline of the plasma jet. The arrangement of the optical probe and the traverse assembly is illustrated schematically in Fig.2. The optical probe can be moved three-dimensionally by using this traverse assembly. In this study, the probe was made to move vertically across the flow field, assumed to be axially symmetrical, in 2 mm intervals. That is, the emission measurement was performed at vertical positions from the center to the outside of the jet. Each measurement started after the pressure in the chamber became stable. The distance between the torch exit plane and the focused point of optical probe, L, was fixed to a specified value before each measurement.



1. Traverse assembly, 2. Optical probe
3. Cryostat, 4. Plasma plume

Fig.2 Traverse assembly and Optical probe

The excitation temperature is determined on the basis of the relative line intensity. That is, the emission collected from the plasma was transmitted to an optical multi-channel analyzer, Hamamatsu PMA-50, through an optical fiber cable. The monochromator in the optical multi-channel analyzer has three kinds of gratings. A 1200 gr/mm holographic grating was mainly used for the present measurements. The data on the emission were calibrated using the relative spectral response of the optical system used here. The excitation temperature T_{ex} at a given vertical position is calculated on the basis of the corrected radiation intensity by using the following equation.

$$\frac{d\left[ln\left\{I_{ji}\lambda_{ji}/\left(g_j A_{ji}\right)\right\}\right]}{dE_j} = -\frac{1}{T_{ex}} \quad (1)$$

The vertical distributions of excitation temperature are obtained from these results.

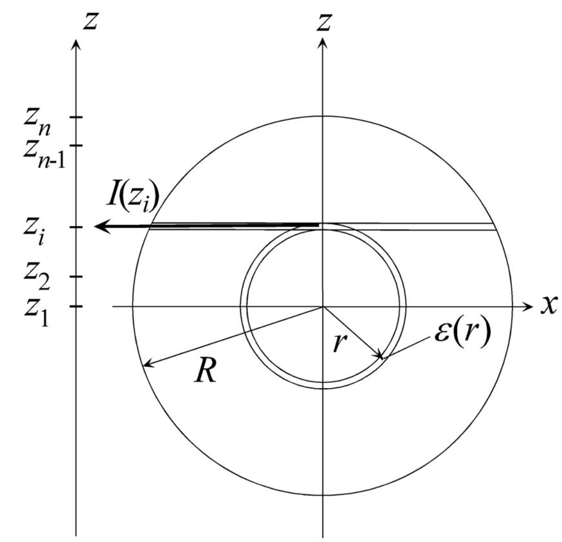


Fig.3 Relationship between the intensity $I(z_i)$ detected at a given vertical position z_i and the radial emission coefficient $\varepsilon(r)$ transformed by Abel-inversion

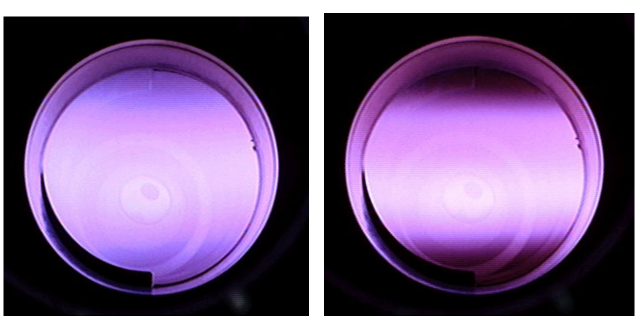
Moreover, the corrected results of the emission intensity measured at the vertical positions are transformed into the radial emission profiles by the Abel-inversion. Figure 3 shows a relationship between the intensity $I(z)$, measured at vertical positions, and the radial emission coefficient $\varepsilon(r)$. When the corrected spectral intensity $I_c(z)$ at a specified wavelength is determined by calibrating the measured intensity $I(z)$ for the spectral response, the emission coefficient $\varepsilon(r)$ is represented by the following expression.

$$\varepsilon(r) = \frac{1}{\pi}\int_r^R \frac{\frac{dI_c(z)}{dz}}{\sqrt{z^2 - r^2}}\, dz \quad (2)$$

The radial temperature distributions are determined on the basis of the relative line intensity method by substituting the transformed emission coefficient instead of the spectral intensity I_{ji} into Eq. (1).

Results and Discussion

The observation of argon plasma jet preceded the relative line intensity measurement to confirm the effect of the strong magnetic field on the jet. Figure 4 illustrates examples of the plasma jet observed through the center window. These images were captured on videotape by using digital video camera. Each image corresponds to the result without and with magnetic field. In the latter case, the magnetic flux density B_c is 1.5 T. These pictures in this figure were shot under the conditions of mass flow rate $\dot{m}$ =1.20 g/s, background pressure p =372 Pa, supplied current to the torch i_s =200A and the distance from the torch exit plane to the focused point of optical probe L = 400mm. It is shown that the plasma in this region compresses evidently with the application of the strong magnetic field. The brightness in the middle of the jet increases with the field strength. It is also clear that the brightness in the middle of the picture for applied magnetic field intensifies in comparison with that for no magnetic field, i.e. B_c = 0 T. However, it was also observed that the jet sometimes deflects from the desired direction. It must be one of the causes that lead to dispersion of data.

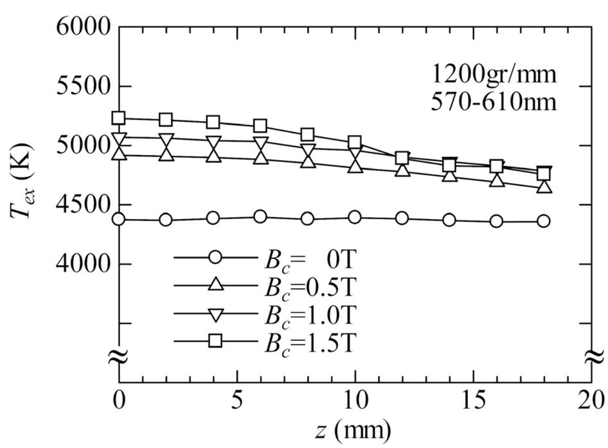


(a) B_c = 0 T (b) B_c = 1.5 T

$\dot{m}$ = 1.20 g/s, p = 372Pa
i_s = 200A, L = 400 mm

Fig.4 Thermal plasma jet observed through center window

The emission measurements were conducted at the opposite side of the center window for observation. The data described here were obtained by scanning the monochromator from 570 to 610 nm in wavelength with the 1200 gr/mm holographic grating. Figure 5 shows the evolution of the excitation temperature with vertical distance from the center of the plasma jet as an example of the effect of the strong magnetic field on the jet. The symbols in the figure denote the determined results based on Argon emission spectra measured at vertical positions and corrected by using the relative spectral response. The measurements were carried out under the conditions of mass flow rate $\dot{m}$ = 1.21±0.02 g/s, background pressure p = 395±15 Pa, supplied current i_s = 100A and the distance L = 400mm. The magnetic flux density B_c applied to the jet was varied from 0 to 1.5T at intervals of 0.5T. The excitation temperature for B_c = 0 T is about 4380 K and shows approximately uniform distribution. When the strong magnetic field is imposed to the jet, the temperature around the central portion of the jet rises and the temperature slope appears obviously in the vertical direction. It is indicated that the abovementioned trend of the temperature distribution and gradient becomes more remarkable as the magnetic flux density B_c increases from 0.5 to 1.5T.

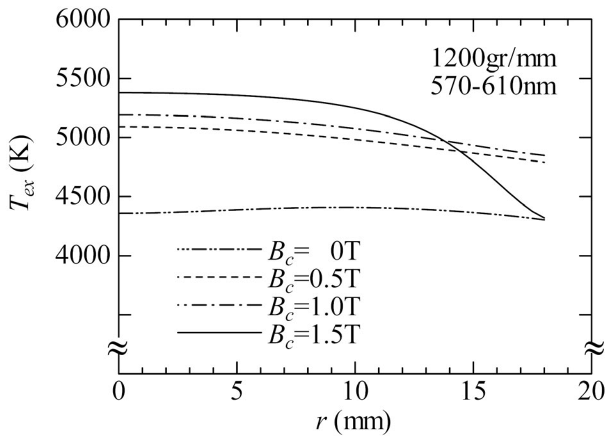


$\dot{m}$ = 1.21±0.02 g/s, i_s= 100A,
p = 395±15 Pa, L = 400 mm

Fig.5 Effect of strong magnetic field on excitation temperature at vertical positions

The data on the emission intensity, employed to determine the excitation temperature distribution in

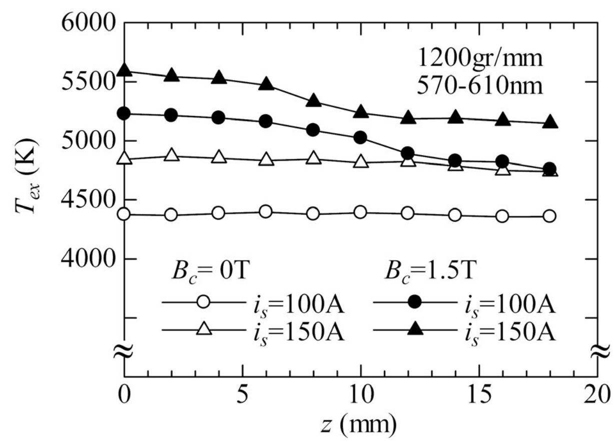
Fig. 5, were also transformed into radial profiles at each wavelength by the Abel-inversion. In the present work, the measured vertical intensity $I(z)$ is assumed to be axisymmetry. Thus, the data on the calibrated intensity $I_c(z)$ are fitted with a polynomial equation of 8th degree. The radial profiles of excitation temperature based on the radial emission profiles are indicated in Fig. 6. The radial temperature profile for B_c = 0 T shows similar tendency to the vertical profile. With the application of the strong magnetic field, the temperature around the central portion of the jet rises as is similar to Fig. 5. The temperature slope becomes steeper as the magnetic flux density B_c increases from 0.5 to 1.5T. These results that are illustrated in Figures 5 and 6 also support the behavior of the plasma jet observed through the center window as shown in Fig.4.



$\dot{m}$ = 1.21±0.02 g/s, i_s = 100A,
p = 395±15 Pa, L = 400 mm

Fig.6 Effect of strong magnetic field on radial temperature distribution

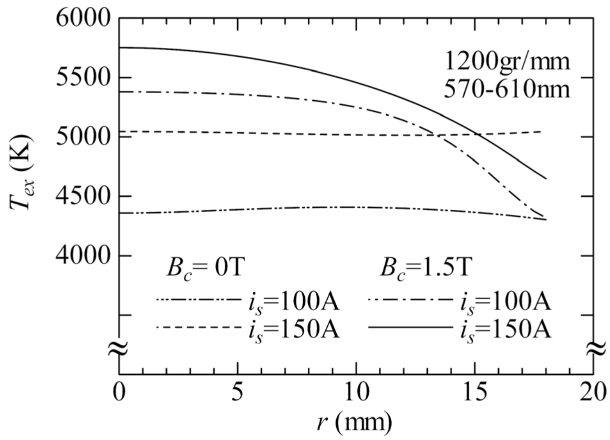
In addition, the effect of the strong magnetic field on the excitation temperature of the jet is examined in the case that the supplied current i_s is specified to be 150A. Figure 7 shows the vertical profiles of the excitation temperature in comparison with that in the case of i_s = 100A. In this figure, the results in the case of the imposed magnetic flux density B_c =1.5T are compared with those in the case of no magnetic field, i.e. B_c = 0 T. The measurements were conducted under the conditions of mass flow rate $\dot{m}$ = 1.21±0.01 g/s, background pressure p = 395±20 Pa and the distance L = 400 mm. The excitation temperature for B_c = 0 T increases with the supplied current i_s and shows almost uniform distribution over the assumed plasma radius. When the strong magnetic field is imposed to the jet, the temperature around the central portion of the jet rises as is similar to that in the case of i_s = 100A. Also, the temperature gradient in the case of B_c =1.5T becomes obviously steep compared with that in the case of B_c = 0 T.



$\dot{m}$ =1.21±0.01 g/s
p=395±20Pa, L=400 mm

Fig.7 Excitation temperature at vertical positions (Effect of supplied current i_s)

The radial profiles of excitation temperature in the case of i_s = 150A are indicated in Fig. 8, in comparison with that in the case of i_s = 100A. The results in this figure are determined from the data employed to obtain the temperature profiles in the vertical direction as shown in Fig.7. In this case, the data on $I_c(z)$ were fitted with a polynomial equation of 8th degree, too. The radial temperature profiles in the case of B_c = 0 T are almost flat although the value of temperature increases with the supplied current i_s. With the application of the strong magnetic field, the temperature around the central portion of the jet in both cases rises as is similar to the vertical temperature profile. The temperature in the radial direction also drops toward the outside of the jet. It is indicated that the results of the excitation temperature distributions do not show obvious difference between conditions of i_s = 100 and 150 A. It is also confirmed from these results shown in Figures 7 and 8 that the state of the plasma jet can be changed by the strong magnetic field as shown in Fig. 4.



$\dot{m}$ =1.21±0.01 g/s
p=395±20Pa, L=400 mm

Fig.8 Radial temperature distribution (Effect of supplied current is)

Conclusions

The effects of the strong magnetic field on the temperature distribution in the plasma jet at a low pressure are studied experimentally by using the relative line intensity measurement. The results obtained here are summarized as follows.

(1) The excitation temperature determined from the relative line intensity measurement at vertical positions rises obviously around the central portion of the jet with the application of strong magnetic field even in the case that the temperature distributions show approximately uniform for no magnetic field. The temperature slope appears obviously in the vertical direction with the strong magnetic field in comparison with the temperature profiles without magnetic field.

(2) It is also clarified from the radial temperature profile based on the Abel-inversion that the temperature around the central portion of the jet rises with the application of strong magnetic field and the temperature gradient increases with the strength of magnetic field. The temperature in the radial direction also drops toward the outside of the jet. It is indicated that the excited temperature around the central part of the jet increases with the strength of magnetic and that the temperature slope toward the outside of the jet becomes obviously large as the field strength increases.

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